Differential measurements of ϕ-meson global spin alignment in Au+Au collisions at STAR

Gavin Wilks[1,*], for the STAR Collaboration

[1]University of Illinois at Chicago, 1200 W Harrison, Chicago, IL 60607, USA

Abstract. The STAR collaboration observed a significant global spin alignment (ρ_{00}) signal for ϕ-mesons in Au+Au collisions using the data from the BES-I [1] which cannot be explained by conventional mechanisms, but may be attributable to the influence of a ϕ-meson force field [2–6]. In this talk, we present differential measurements of ϕ-meson global spin alignment using the STAR detector in Au+Au collisions at $\sqrt{s_{NN}}$ = 14.6 and 19.6 GeV from the second phase of the Beam Energy Scan at RHIC (BES-II). The first rapidity (y) dependent ρ_{00} results for ϕ-mesons will be shown, alongside new centrality and transverse momentum (p_T) dependent measurements. The results presented in these proceedings will help understand the potential link of global spin alignment to vector meson fields and their roles in the evolution of nuclear matter.

1 Introduction

In non-central heavy-ion collisions, a large orbital angular momentum is produced, generating vorticity of the Quark Gluon Plasma (QGP) along the orbital angular momentum axis. Through spin-orbit couplings [7], a particle's spin can be polarized, known as global polarization. The global polarization of $\Lambda(\bar{\Lambda})$ hyperon can be used as a probe of $s(\bar{s})$ global polarization since, according to the flavor-spin wave function, the $\Lambda(\bar{\Lambda})$ polarization is carried solely by the $s(\bar{s})$ [8]. Recent measurements from the STAR collaboration show a significant signal of $\Lambda(\bar{\Lambda})$ hyperon global polarization [9].

Following the quark coalescence model, the production of ϕ-mesons ($s\bar{s}$) should be affected by the global polarization of the $s(\bar{s})$ [2]. In $\Lambda(\bar{\Lambda})$ hyperon decay, the global polarization can be measured since they decay through the weak force with parity violation, where decay products are preferentially emitted along the spin direction. However, for ϕ-mesons ($s\bar{s}$) which decay through the strong force with parity conservation, a direct measurement of spin polarization is not feasible. Rather, we can indirectly study global polarization using global spin alignment, measured by the ρ_{00} diagonal element of the spin density matrix. For the decay $\phi \to K^+K^-$, the K^+ or K^- daughter's polar angle (with respect to the spin-quantization axis) (θ^*) distribution within the ϕ-meson rest frame is given by:

$$\frac{dN}{d(\cos\theta^*)} \propto (1-\rho_{00}) + (3\rho_{00}-1)\cos^2\theta^*. \quad (1)$$

If $\rho_{00} \neq 1/3$, then the ϕ-meson spin states are not equally probable, leading to an anisotropic polar angle distribution of the daughter kaon. In the case of $\rho_{00} > 1/3$, the occupation of the

*e-mail: gwilks3@uic.edu

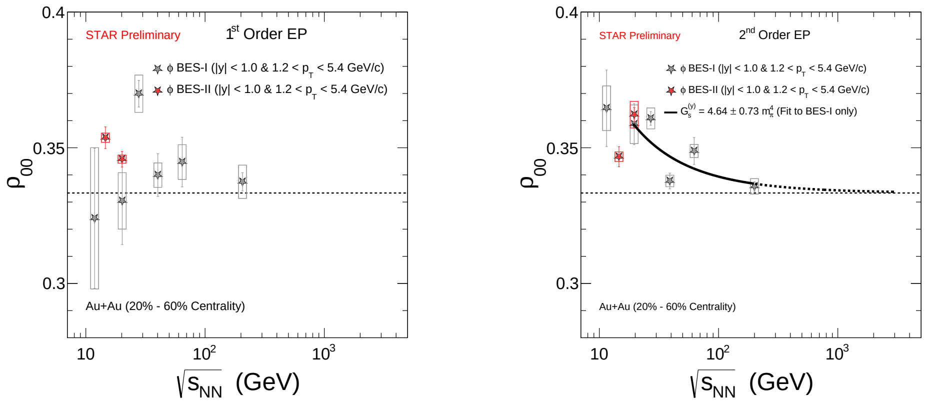

Figure 1. $\sqrt{s_{\mathrm{NN}}}$ dependent ϕ-meson ρ_{00} for 20-60% centrality Au+Au collisions. Details about the fit can be found in [1].

spin-0 state is more probable, which corresponds to an alignment of the ϕ-meson's average polarization along the spin-quantization axis [10, 11].

Recent STAR measurements [1] reported a significant signal ($\rho_{00} > 1/3$) for ϕ-mesons in mid-central Au+Au collisions from the first phase of the Beam Energy Scan at RHIC (BES-I) at energies below $\sqrt{s_{\mathrm{NN}}}$ = 62.4 GeV. No conventional physical mechanism can explain the scale of the measured ρ_{00} signal, but it was proposed that fluctuations of the theoretical ϕ-meson strong force field could accommodate this signal [2]. If fully established, this possible connection between the ϕ-meson field and global spin alignment could allow us to probe previously inaccessible features of this field. In these proceedings, we report measurements of ϕ-meson ρ_{00} in Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 14.6 and 19.6 GeV from the second phase of the Beam Energy Scan at RHIC (BES-II). BES-II provides significantly larger data samples, allowing for more precise measurements and differential studies not previously possible with BES-I data. Our precision is further increased by the many upgrades made to the STAR detector prior to BES-II, including the Event Plane Detector (EPD) [12] and an improved inner Time Projection Chamber (iTPC) [13].

2 Results and discussion

In this analysis, we use the orbital angular momentum direction in each event as the spin-quantization axis. To identify the orbital angular momentum axis, we use the normal of the reaction plane spanned by the impact parameter vector and the direction of the incoming colliding nuclei. To estimate the reaction plane, we can calculate the first- and second-order harmonic event planes through the methods detailed in [14]. The TPC ($|\eta| < 1.5$) is used to extract the second order event plane, and the EPD ($2.1 < |\eta| < 5.1$) is used for the first order event plane. We used both the first- and second-order harmonic event planes separately to calculate the θ^{*} angle of the K^{+} daughter, providing two measurements of the ϕ-meson global spin alignment.

The collision energy dependence of ϕ-meson ρ_{00} is shown in Figure 1 for mid-central (20-60% centrality) Au+Au collisions from BES-II. We show new results for $\sqrt{s_{\mathrm{NN}}}$ = 14.6 GeV with $\rho_{00} > 1/3$ and consistency with BES-I for $\sqrt{s_{\mathrm{NN}}}$ = 19.6 GeV for measurements using both the first- and second-order event planes. The increased sample size increases our precision leading to a more significant measurement of $\rho_{00} > 1/3$ at 19.6 GeV. The solid line fit is derived from the ϕ-meson strong force field model. Details can be found in [1, 2, 6].

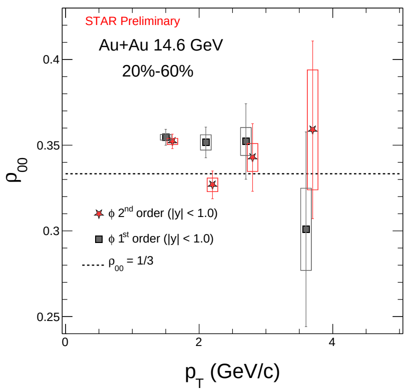

Figure 2. p_T dependent ϕ-meson ρ_{00} for 20-60% centrality BES-II Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 14.6 GeV.

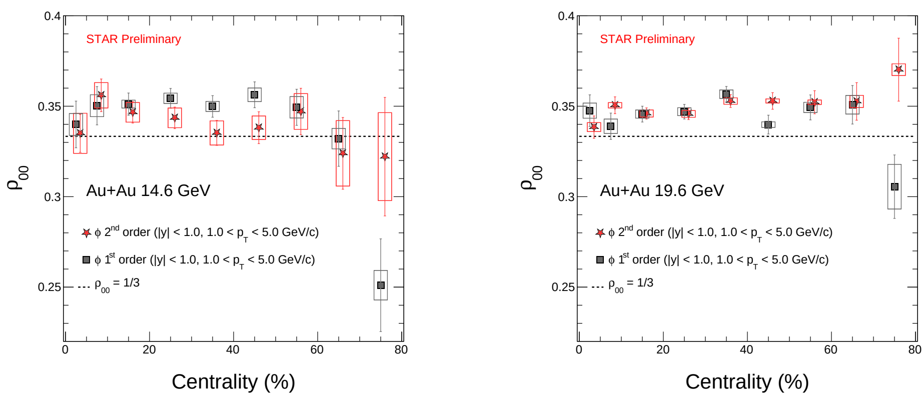

Figure 3. Centrality dependent ϕ-meson ρ_{00} for BES-II Au+Au collisions at $\sqrt{s_{\rm NN}}$ = 14.6 GeV and 19.6 GeV.

Figure 2 shows the p_T dependent ϕ-meson global spin alignment where no significant p_T dependence is observed. The centrality dependent ρ_{00} is shown in Figure 3 and there is no significant centrality dependence for 14.6 or 19.6 GeV. This contrasts to results of $\Lambda(\bar{\Lambda})$ polarization where a strong dependence on centrality is seen [15, 16]. This is unsurprising since the physical mechanisms driving $\Lambda(\bar{\Lambda})$ polarization are not expected to have significant contributions to ϕ-meson ρ_{00}; therefore, we do not necessarily expect the same centrality dependence [2]. Figure 4 shows the first rapidity dependent ϕ-meson ρ_{00} measurements. In both 14.6 GeV and 19.6 GeV collisions we observe $\rho_{00} = 1/3$ at mid-rapidity ($|y| = 0$) and an increase as $|y|$ approaches 1. Predictions of the $|y|$ dependence were made in [4] following directly from the ϕ-meson strong force field model discussed in [2, 6]. These predictions well describe the data for $|y| > 0.5$, but fail to do so for $|y| < 0.5$. In this model, the current understanding is that anisotropies in the ϕ-meson field fluctuations could cause ρ_{00} to deviate from 1/3 and these anisotropies in the ϕ-meson rest frame are affected by the motion of the ϕ-meson in the global frame.

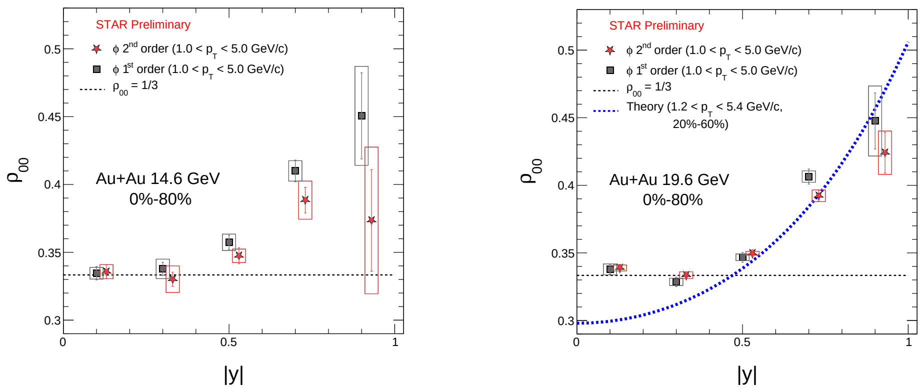

Figure 4. Rapidity dependent ϕ-meson ρ_{00} for 0-80% centrality BES-II Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 14.6 GeV and 19.6 GeV. The dashed blue line represents the prediction from the ϕ-meson strong force field model in [4].

3 Conclusion

In these proceedings, we presented ϕ-meson ρ_{00} measurements with respect to the first- and second-order event planes for Au+Au collisions at $\sqrt{s_{\mathrm{NN}}}$ = 14.6 and 19.6 GeV from BES-II. We have new results for 14.6 GeV and our integrated values of ϕ-meson ρ_{00} for 19.6 GeV are consistent between BES-I and BES-II data. We observe no significant dependence of ρ_{00} on p_T or the collision centrality. Regarding the first measurements of the rapidity dependent ϕ-meson ρ_{00}, we observe an increasing ρ_{00} for rapidity ($|y| > 0.5$), consistent with the current ϕ-meson strong force field model [4]. We also see no significant difference between the first- and second-order event plane methods. In further studies, we will include more collisions energies from BES-II and expand the $|\eta|$ acceptance.

References

[1] STAR Collaboration, Nature **614** 244-248 (2023).
[2] Sheng et al., Phys. Rev. D **101**, 096005 (2020).
[3] Sheng et al., Phys. Rev. D **105**, 099903 (2022).
[4] Sheng et al., Phys. Rev. C **108**, 054902 (2023).
[5] X.L. Sheng et al., Physical Review Letters **131**, 042304 (2023).
[6] Sheng et al., Phys. Rev. D **102**, 056013 (2020).
[7] Liang et al., Phys. Lett. B **629**, 20–26 (2005).
[8] Close, *An Introduction to Quarks and Partons*, Academic Press (1979).
[9] STAR Collaboration, Nature **548**, 62–65 (2017).
[10] Schilling et al., Nucl. Phys. B **18**, 332 (1970).
[11] Chen et al., Science Bulletin **68** 874–877 (2023).
[12] STAR Collaboration, STAR Note 619, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0619
[13] STAR Collaboration, STAR Note 666, https://drupal.star.bnl.gov/STAR/starnotes/public/sn0666
[14] Poskanzer et al., Phys. Rev. C **58**, 1671–1678 (1998).
[15] STAR Collaboration, Phys. Rev. C **98**, 014910 (2018).
[16] STAR Collaboration, arXiv:2305.08705 (2023).